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Phase change material selection for two innovative compact energy storage systems in residential buildings

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ABSTRACT

Within the framework of HYBUILD, an EU Horizon 2020-funded project, two innovative compact hybrid electrical/thermal storage systems for stand-alone and district connected residential buildings will be developed and tested in three demos located in Spain, France, and Cyprus. One of the innovative systems is aimed to be placed in buildings located in Mediterranean climate regions, where cooling loads are dominant, while the other system is intended for Continental climate regions, where the heating demand is dominant. Each system will include, among others components such as a sorption storage system and domestic hot water tanks, a latent thermal energy storage (LTES) system that will be connected to a heat pump through an innovative heat exchanger made of aluminium and filled with phase change material (PCM). In both cases, the heat pump works with electricity provided by a photovoltaic system that is, at the same time, connected to an electrical storage battery. The aim of using the LTES system is to enhance the use of solar energy, which will be translated into a reduction of the building energy consumption and related costs. This study focuses on the selection of the most suitable PCM to be used in each system. On the one hand, the LTES system of the Mediterranean system will be used to store cold to reduce the cooling demand. Taking into account that, according to the design parameters, the heat pump will require a refrigerant evaporation temperature around 2 ºC, and the building cooling system will require water supply in the range from 7 ºC to 12 ºC, the PCM melting temperature range should be within 0 ºC and 7 ºC. On the other hand, the LTES system of the Continental system will be used to store heat to reduce the domestic hot water (DHW) demand. The LTES will be located at the compressor outlet and will be charged by the hot refrigerant that exits the compressor at temperatures as high as 120 ºC. During the discharge process, the heat stored in the LTES will be supplied to the DHW at a temperature in the range between 50 ºC to 55 ºC. As a consequence, the range for the PCM melting temperature investigated in this case should be between 62 ºC and 68 ºC. Besides the melting temperature, other selection criteria considered include the PCM melting enthalpy and melting range, maximum allowed working temperature, density, thermal conductivity, availability, cost, and compatibility with aluminium. To decide the ideal PCM candidate for each system, a decision matrix was defined and used, by applying a weighted score to the selection criteria items according to their importance. The preliminary results indicate that for the Mediterranean system the best candidate is the commercial savE OM3 PCM, while for the Continental system, another commercial product PureTemp 63 is the most adequate option.

Keywords: Phase change material; heating and cooling; thermal energy storage, material selection.

1. Introduction

As a consequence of one of the initiatives of the European Commission (European Commission 2016) to support the integration of renewables in buildings and increase the self-consumption, the HYBUILD H2020 project (HYBUILD 2017) was launched in October 2017 to investigate the feasibility of implementing two innovative compact hybrid electrical/thermal energy storage systems aimed to reduce the energy consumption of stand-alone and district connected buildings. The reduction of energy consumption of the buildings will be achieved by means of PV panels that will provide part of the energy needed by the HVAC system of the building. One of the two systems is aimed to be used in Mediterranean climate for which the cooling demand is relevant, while the other system is mainly intended for Continental climate, where the heating season operation is dominant. To increase the use of solar energy both systems are equipped with both an electrical and a thermal energy storage system. In this way, when solar energy is not available, the systems can operate by using the electrical and/or thermal energy stored during the periods of high solar energy availability.

The Mediterranean concept contains a latent heat thermal energy storage (LHTES) based on the use of phase change material (PCM) to store the cold produced by the compression heat pump that is directly connected by means of a DC bus to the PV panels. The PCM is implemented on the low-pressure side of the refrigeration system within a three-fluid heat exchanger in which direct contact between the refrigerant, the PCM, and the heat transfer fluid (HTF) of the house cooling loop, and is achieved. Therefore, the phase change temperature of the PCM used in the Mediterranean system should be low enough (around 5 ºC) to ensure a proper storage of the cold produced by the refrigeration system. The Mediterranean system will be installed and tested in two different demo sites in Spain and Cyprus.

The Continental system works under the same concept as the Mediterranean one, although in this case the LHTES is located at the compressor discharge to store the heat during periods of high solar radiation availability, and use it for space heating and/or domestic hot water (DHW) production when needed. Since in this case the LHTES is charged by the hot refrigerant gas at the compressor outlet, a much higher PCM phase change temperature (around 60 ºC) is required in this case. The Continental system will be installed and tested in a demo site in France.

The PCM selection procedure becomes a crucial step for the optimum operation of the LHTES prototype and the associated thermal processes. An important aspect within this procedure is the identification of the critical parameters and requirements, which are not always easy to identify. The phase change temperature and enthalpy are the most widely used selection criteria for LHTES systems. However, other properties such as health hazard, corrosion, cost, availability of the material, and thermal and cycling stability should also be taken into account to extend these selection criteria (Miró et al. 2016, Gasia et al. 2017). The methodology for a proper PCM selection proposed by Miró et al. 2016 and Gasia et al. 2017 requires a high number of experiments such as thermal and cycling stability tests. Therefore, a preliminary selection based on information provided by the PCM supplier is needed before a deeper experimental analysis of the most promising PCM candidates is performed.

The objective of this contribution is to present the methodology applied to select the most appropriate PCM to be used in the LHTES of the Mediterranean and of the Continental systems as well as to show the preliminary results obtained so far.

2. Methodology

2.1 Description of the LHTES

The LHTES that will be used in both systems consists of a refrigerant/PCM/water heat exchanger (RPW-HEX) made of aluminium, which contains several mini-channel (MPE) tubes on the refrigerant side and a shell with offset strip fins on the HTF and the PCM sides. The presence of a fin structure inside the PCM channels of the RPW-HEX allows heat transfer between the refrigerant that evaporates within the heat exchanger and the HTF, while the PCM can be charged by the refrigerant or discharged by the HTF depending on the building cooling demand.

An image of the heat exchanger is shown in Figure 1. Similar heat exchangers without PCM were developed in the framework of a previous FP7 project by the German company AKG, which is one of the 21 partners of the project HYBUILD. An optimal design of the RPW-HEX is needed by means of numerical simulations and experimental tests, which will first be performed using small-scale prototypes that should help in calibrating the numerical models. Based on these preliminary results, AKG will manufacture the adequate RPW-HEX modules with the most suitable choice of fin structures to be used for the water and PCM passages.

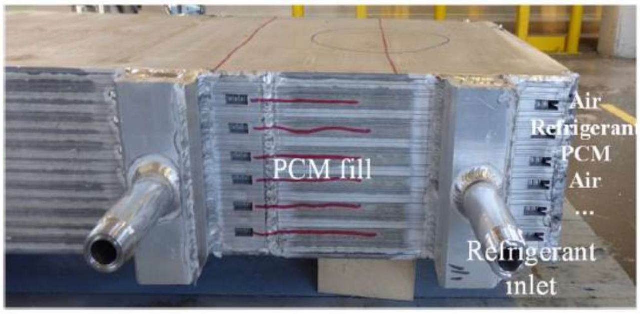

Figure 1. Photo of the heat exchanger for refrigeration dryer with integrated PCM storage.

2.2 Literature review of suitable PCM candidates

As a first step of the selection methodology, a literature review was performed taking into consideration both requirements of the systems, and general requirements that should be fulfilled by any suitable PCM. On the one hand, the system requirements restrict the phase change temperature, the maximum temperature that the PCM must stand, and its compatibility with aluminium. On the other hand, the general features that should usually be fulfilled by a PCM are: high phase change enthalpy, narrow phase change range, low or no subcooling, no hysteresis, high thermal conductivity, high density, availability, no or low toxicity, and low cost. The characteristics of the boundary conditions and the operating temperatures of the LHTES systems that are going to be used in both systems require that the selected PCM have a phase change temperature ranged between 0 ºC and 7 ºC for the Mediterranean concept, and between 48 ºC and 68 ºC for the Continental concept.

2.2.1. PCM for the Mediterranean system (low temperature)

Currently, there are few reviews in the literature covering the temperature range for the Mediterranean system (Oró et al. 2012; Veerakumar, Sreekumar 2016). Moreover, not all existing PCM within this range are available in these reviews. Therefore, in order to broaden and gather all existing PCM with a phase change temperature between 0 ºC and 7 ºC, a new literature review was done.

Around 60 PCM candidates with a phase change temperature in this temperature range were found. Given the relatively large number of possible PCM candidates, a pre-selection was performed in order to discard those PCM that could not be selected taking into account some properties such as health hazard, corrosion with aluminium, availability, or phase change enthalpy. Moreover, only those PCM with phase change temperature close to the most desirable phase change temperature range (around 2 ºC to 4 ºC) were taken into account. The pre-selected PCM candidates for the Mediterranean system are shown in Table 1.

2.2.2. PCM for the Continental system (medium temperature)

A literature review was also done to find suitable PCM candidates for the Continental LHTES system, with melting temperature in the range between 48 ºC and 68 ºC. As a result, more than 120 PCM potential candidates were found, which is even much higher than the number found in the Mediterranean case. Therefore, a pre-selection was also applied in this case to first discard those PCM candidates that were either corrosive with aluminium, or had very low phase change enthalpy, or bad thermo-physical properties, or were not available. Likewise, in the case of different PCM of similar type or properties, only the most suitable of them were pre-selected. The pre-selected PCM candidates for the Continental system are shown in Table 2.

Table 1: List of pre-selected available PCM for the Mediterranean system and some of their thermophysical properties

Commercial name/Composition	**Type**	**T_m (ºC)**	**ΔH (kJ/kg)**	**k (W/m·K)**	**ρ (kg/m³)**	**Reference**
RT3HC_1	Organic (paraffin)	1-3	190	0.20 (l) 0.20 (s)	770 (l) 880 (s)	(Rubitherm 2019)
A3	Organic (n.a.)	3	200	0.210	765	(PCMproducts 2019)
0200- Q2 BioPCM	Organic (bioPCM)	2	200-230	0.2-0.7 (l) 0.25-2.5 (s)	850-1300 (l) 900-1250 (s)	(PCES 2019)
PCM-PDR03P	Organic (n.a.)	3.5	185	n.a.	570	(RGEES 2019)
savE OM 03	Organic (n.a.)	3.5	229	0.224 (l) 0.146 (l)	835 (l) 912 (s)	(PLUSS 2019)
Caprylic acid + lauric acid (9:1 by mol)	Organic eutectic (fatty acid)	3.8	151.5	n.a.	n.a.	(Shengli, Dong, Deyan 2005)
RT4	Organic (paraffin)	2-4	175	0.20 (l) 0.20 (s)	770 (l) 880 (s)	(Rubitherm 2019)
0200- Q4 BioPCM	Organic (bioPCM)	4	200-230	0.2-0.7 (l) 0.25-2.5 (s)	850-1300 (l) 900-1250 (s)	(PCES 2019)
PureTemp 4	Organic (biobased)	4	195	n.a.	n.a.	(PureTemp 2019)
Tetrahydrofuran clathrate hydrate	Inorganic (clathrate hydrate)	4.4	255	n.a.	n.a.	(Jankowski, McCluskey 2014a)

n.a. – not available

Table 2: List of pre-selected available PCM for the Continental system and some of their thermophysical properties

Commercial name/Composition	**Type**	**T_m (ºC)**	**ΔH (kJ/kg)**	**k (W/m·K)**	**ρ (kg/m³)**	**Ref.**
A50	Organic (n.a.)	50	218	0.18	810	(PCMproduct s 2019)
0500- Q50 BioPCM	Organic (bioPCM)	50	200-230	0.2-0.7 (l) 0.25-2.5 (s)	850-1300 (l) 900-1250 (s)	(PCES 2019)
savE OM50	Organic (fatty acids mixture)	50-51	223	0.14 (l) 0.21 (s)	859 (l) 961 (s)	(PLUSS 2019)
RT54HC	Organic (paraffin)	53-54	200	0.2	800 (l) 850 (s)	(Rubitherm 2019)
Stearic acid ($CH_3(CH_2)_{16}$-COOH)	Organic (fatty acid)	54	157	0.17 (l) 0.29 (s)	940 (s)	(Pereira da Cunha, Eames 2016)
Cetyl stearate	Organic (ester)	54.6	212.1–216.3	n.a.	n.a.	(Jankowski, McCluskey 2014b)
savE OM 55	Organic (mixture of fatty acids)	55	208	0.16 (l) 0.1 (s)	841 (l) 935 (s)	(PLUSS 2019)
0500- Q56 BioPCM	Organic (bioPCM)	56	200-230	0.2-0.7 (l) 0.25-2.5 (s)	850-1300 (l) 900-1250 (s)	(PCES 2019)
Tristearin ($(C_{17}H_{35}COO)_3C_3H_5$)	Organic	56	190.8	n.a.	862 (l)	(Jankowski, McCluskey 2014b)
PureTemp 58	Organic (bio-based)	58	225	0.15 (l) 0.25 (s)	810 (l) 890 (s)	(PureTemp 2019)

Table 3: List of pre-selected available PCM for the Continental system and some of their thermophysical properties (*continued*)

Commercial name/Composition	Type	T_m (ºC)	ΔH (kJ/kg)	k (W/m·K)	ρ (kg/m³)	Ref.
A58H	Organic (n.a.)	58	243	0.18	820	(PCMproducts 2019)
66.7% Polyethylene oxide 10000 + 33.3% Myristic acid	Organic (plastic + fatty acid)	58.7	191	n.a.	n.a.	(Pielichowska , Pielichowski 2014)
Climsel C58	Inorganic (salt hydrate)	58	259	1.46	n.a.	(Mehling, Cabeza 2008; Zalba et al. 2003)
		55-58	260	0.47 (l) 0.57 (s)	1400	(Climator 2019)
		58	80	0.5–0.7	1460	(Kenisarin, Mahkamov 2016a)
Paraffin C_{22}–C_{45}	Organic (paraffin)	58–60	189	0.21	795 (l) 920 (s)	(Sharma et al. 2009)
Paraffin C27	Organic (paraffin)	58.8	236	n.a.	n.a.	(Sharma et al. 2009)
RT60	Organic (paraffin)	58–60	214	0.2	n.a.	(Kenisarin, Mahkamov 2016b)
Stearyl stearate	Organic (ester)	59.2	214.75–214.93	n.a.	n.a.	(Jankowski, McCluskey 2014b)
PureTemp 63	Organic (bio based)	63	206	0.15 (l) 0.25 (s)	840 (l) 920 (s)	(PureTemp 2019)
RT64HC	Organic (n.a.)	63-65	250	0.2	780 (l) 880 (s)	(Rubitherm 2019)
Stearyl arachidate ($C_{38}H_{76}O_2$)	Organic (ester)	64.96	226	n.a.	2350 (l) 1930 (s)	(Jankowski, McCluskey 2014b)
50% CH_3CONH_2 + 50% $C_{17}H_{35}$ COOH	Organic (eutectic)	65	218	n.a.	n.a.	(Sharma et al. 2009)
0500- Q65 BioPCM	Organic (bioPCM)	65	200-230	0.2-0.7 (l) 0.25-2.5 (s)	850-1300 (l) 900-1250 (s)	(PCES 2019)
savE FS 65	Organic (blend of organic material in polymer matrix)	66-68	218	0.25 (s)	842 (s)	(PLUSS 2019)
PureTemp 68	Organic (bio based)	68	213	0.15 (l) 0.25 (s)	870 (l) 960 (s)	(PureTemp 2019)
0500- Q68 BioPCM	Organic (bioPCM)	68	200-235	0.2-0.7 (l) 0.25-2.5 (s)	850-1300 (l) 900-1250 (s)	(PCES 2019)

2.3 PCM selection methodology

The second step of the selection method consisted in the development of a decision matrix, taking into account the following parameters: phase change range, melting enthalpy, availability, price, and maximum temperature in the case of the Continental system. These parameters were chosen because of their direct impact on the system viability from the operational and economic points of view, and the relative easiness in obtaining their values. A score was given to each of the PCM candidate for each of the above decision parameter, and a total score was calculated based on a weighted average. The weight percentage assigned to each parameter was selected based on the importance that the authors considered they could have on the final decision. However, a sensibility analysis is required to study the influence of varying the different weights on the results, which will be performed in a separate paper currently in preparation.

2.3.1.Mediterranean system

A score was given to each of the PCM candidate for each of the above decision parameter, and a total score was calculated based on a weighted average. The weighted percentage coefficients assigned to the decision parameters are listed in Table 4. The score given to each of the decision parameter was calculated taking into account the criteria shown in Table 5.

Table 4. The weighted percentage coefficients assigned to each decision parameter.

Decision parameter	Weight percentage (%)
Phase change temperature range (Cp-T curve)	30
Enthalpy	35
Availability	10
Price	25
Total	100

Table 5. The scoring criteria applied to each decision parameter.

Temperature range (ºC)		Enthalpy (kJ/kg)		Availability		Price (€/kg)	
<2	3	>250	3	Yes	3	<2.5	3
2<T<3	2	200<h<250	2	No	0	2.5<P<5	2
3<T<4	1	150<h<200	1	---	---	5<P<10	1
>4 or n.a.	0	<150 or n.a.	0	---	---	>10 or n.a.	0

2.3.2.Continental system

A score was given to each of the PCM candidate for each of the above decision parameter, and a total score was calculated based on a weighted average. The weighted percentage coefficients assigned to the decision parameters are listed in Table 6.

Table 6. The weighted percentage coefficients assigned to each decision parameter.

Decision parameter	Weight percentage (%)
Phase change temperature range (Cp-T curve)	30.00
Enthalpy	18.75
Availability	7.50
Price	18.75
Maximum working temperature	25.00
Total	100.00

To score given to each of the decision parameter was calculated taking into account the criteria shown in Table 7.

Table 7. The scoring criteria applied to each decision parameter.

Temperature range (ºC)		Enthalpy (kJ/kg)		Availability		Price (€/kg)		Maximum temperature (ºC)	
<2	3	>250	3	Yes	3	<2.5	3	>120	3
2<T<3	2	250<h<200	2	No	0	2.5<P<5	2	<120 or n.a.	0
3<T<4	1	200<h<150	1	---	---	5<P<10	1	---	---
>4 or n.a.	0	<150 or n.a.	0	---	---	>10 or n.a.	0	---	---

3. Results and discussion

3.1 Mediterranean system

The results of applying the decision matrix described in the previous section are shown in Figure 2. For the temperature range of interest, the best candidate is the savE OM 03 commercial product from PLUSS® (PLUSS 2019), a manufacturer from India. However, since the transportation costs and any potential additional costs were not taken into consideration in the decision matrix, the results may be different and the best solution can consequently also change. Therefore, a future and more exhaustive analysis is required to take a final decision regarding the most suitable PCM to be used in the Mediterranean system. A promising alternative to the savE OM 03 candidate is RT4 from Rubitherm.

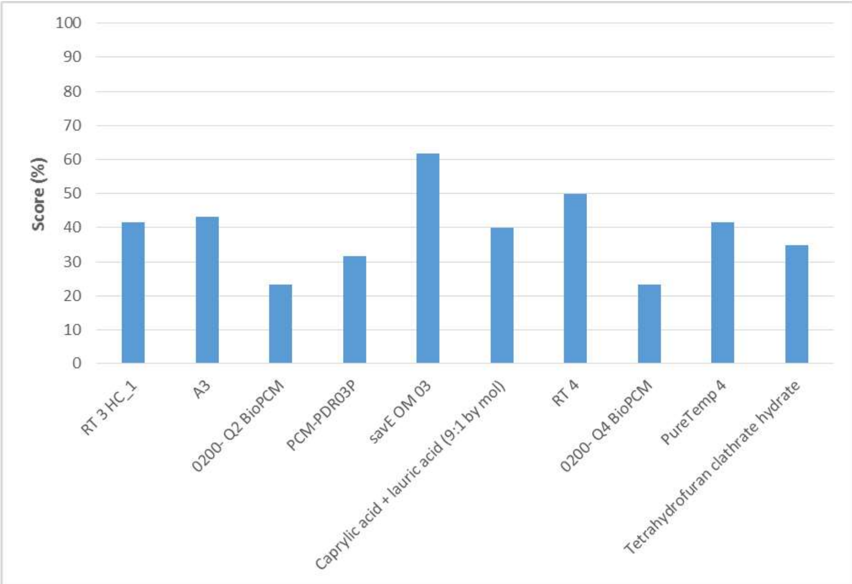

Figure 2. Score obtained by each of the pre-selected PCM candidate for the Mediterranean system

3.2 Continental system

The results of applying the decision matrix described in the previous section to all the PCM candidates for the Continental system listed in Table 2 are shown in

Figure 3.

According to the latest simulations performed to determine the most adequate temperature range for the PCM to be used in the Continental LHTES, the results indicate that the temperature range of interest should be around 65 ºC. Therefore, the best candidate with phase change around this temperature is the commercial PureTemp 63 product, which is a bio-based PCM produced by Entropy Solution, LLC a company from the United States (PureTemp 2019). However, it has to be mentioned that the final results would be different if RT64HC PCM from Rubitherm would be able to stand a maximum temperature of 120 ºC, which may be the case despite the fact that, according to its data sheet (Rubitherm 2019), this PCM can only be used at temperatures up to 95 ºC. It is therefore crucial to perform further analysis of some of the thermophysical properties of the best two PCM candidates, such as cycling tests and thermogravimetric analysis, to confirm which of the two best candidates can stand temperature up to 120 ºC. If the future results would confirm that the RT64HC PCM from Rubitherm could work up to 120 ºC, then this PCM would be the best option. Furthermore, as in the case of the Mediterranean system, transportation costs and other potential additional costs should also be taken into consideration in the decision matrix to help in taking the final decision.

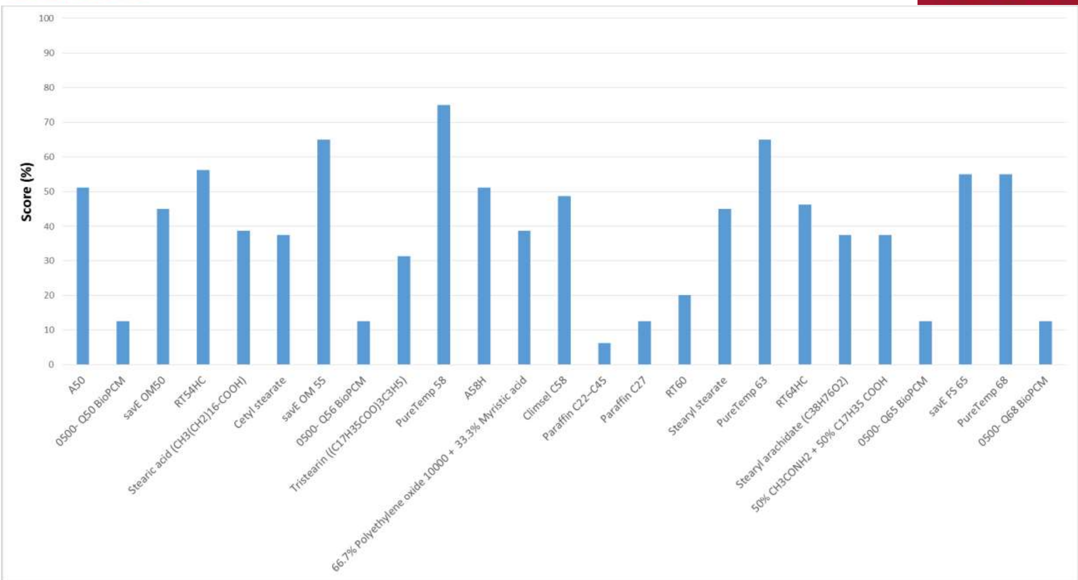

Figure 3. Score obtained by each of the pre-selected PCM candidate for the Continental system

4. Conclusions

Integration of renewables energies to increase self-consumption in buildings is one of the initiatives supported by the European Commission. An example of such an initiative is HYBUILD, a project funded through the Horizon 2020 programme, whose main objective is to develop two innovative compact hybrid electrical/thermal storage systems for stand-alone and district connected residential buildings. The concepts will be tested in three demos located in Spain, France, and Cyprus. The first concept was specially designed to be used in Mediterranean climate regions, while the second concept was designed to be used in Continental climate regions. Among other key components, each of the two systems will include a latent thermal energy storage system placed in the heat pump circuit. The Mediterranean system requires a low-temperature PCM with phase change temperature between 2 ºC to 4 ºC, while the Continental system should work with a PCM with phase change temperature around 65 ºC.

In this work, the methodology proposed to determine the most suitable PCM to be used in each case was presented. Following a literature review of all PCM candidates in the temperature ranges of interest, a decision matrix was defined and used to evaluate the most promising PCM candidates, which were pre-selected based on some crucial properties such as melting enthalpy and melting range, maximum allowed working temperature, density, thermal conductivity, availability, cost, and compatibility with aluminium. Out of the 10 PCM candidates pre-selected for the Mediterranean system, the preliminary results indicated that the most promising one was the commercial savE OM3 (PLUSS 2019) PCM from the Indian company Pluss, while for the Continental system the commercial product PureTemp 63 (PureTemp 2019) from the Entropy Solution LLC American company is the most adequate option.

A further detailed analysis is needed to take the final decision regarding the best option for the PCM selection for both systems, based on detailed information regarding additional acquisition costs and results from the cycling and TGA tests that will be performed.

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